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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Describes the birefringent coating technique of photoelastic evaluation of
surface stress. Included are test equipment and instrumentation, calibration
tests, static and dynamic loading, and photographic requirements.

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

DRSTE-RP-702-100   28 August 1980
Test Operations Procedure 1-2-605
AD No.

BIREFRINGENT COATING TECHNIQUE, PHOTOELASTIC STRESS ANALYSIS

1.   SCOPE. This TOP describes the birefringent coating technique for evaluating surface stress. Included are static and dynamic loading tests.

2.   FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

ITEM	REQUIREMENT
Heated shelter	Large enough to cover test item; must be capable of maintaining a temperature of at least 13°C
Paint-removal facility	Accessible
Frame/fixture (as necessary to restrain test item externally)	Designed with a safety factor of 5
High-speed cameras	16-mm movie camera and 35-mm still camera
Machinist's level (or equivalent)	15 cm

ITEM (CONT'D)	REQUIREMENT (CONT'D)
Contouring mold (Teflon sheet with adhesive backing on a steel plate 1 by 25 by 25 cm; see Figure A-1, Appendix A)	Flat, within $\pm$0.08 mm

.2.2 Instrumentation.

ITEM	MAXIMUM ERROR OF MEASUREMENT*
Tensile testing machine	$\pm$1% of maximum load on scale
Temperature-measuring devices (to measure ambient air temperature and temperatures of liquid plastic)	$\pm$1°C
Micrometer (deep throat, curved anvil, with 9.5-mm radius)	$\pm$0.025 mm
Reflection polariscope	$\pm$0.01 fringe; $\pm$2° principal strain direction
Weight scale (maximum 500-gram capacity)	$\pm$0.05 gram

3.   PREPARATIONS FOR TEST.

     a.   Select birefringent liquid plastic (a resin plus a hardener) for photoelastic application, on the basis of sensitivity, etc.

     b.   Follow the manufacturer's instructions for preparing the contour mold (Figure A-1, Appendix A), mixing the resin and hardener, and removing the birefringent plastic from the contouring mold. NOTE: If, during the formation and curing process, the plastic becomes damaged and such damage would affect test results, discard and formulate new plastic without flaws or damage.

3.1 Calibration Test. Select calibration specimens (aluminum or steel bars 1 by 3 by 31 cm) representative of test item material. Calibrate the device used to evaluate stress. Do not perform the calibration test with loads that will exceed the plastic limit of the aluminum/steel bars. All measurements of the fringe order for the calibration test should be made at the center of the calibration strip. The photoelastic equipment used to determine the fringe orders during testing is also used to determine fringe order in the calibration test.

*Values may be assumed to represent $\pm$2 standard deviations; thus, the stated tolerances should not be exceeded in more than 1 measurement of 20.

a. Cut a strip of birefringent plastic 3 by 8 cm from each sheet of plastic; remove it from the contouring mold; lay it flat on the calibration specimen and allow to harden. Cement the plastic to the calibration strip.

b. Prepare the tensile testing machine to apply tension loads to each end of the calibration specimen. Mount the bar in a vertical position so that no part of the plastic or cement touches the fixture of the tensile testing machine.

c. From a zero load condition on the calibration specimen, increase the load of the tensile testing machine in increments, so that the difference in fringe order between each increment is about one half. The maximum fringe order observed should not exceed 2.5.

3.2 Test Item.

a. Select surface ares(s) of the test item to be examined by the photoelastic method. These areas should include, but not be limited to, corners, welds, areas around edges of holes, near fasteners (but not touching them), near points of loading, and near other areas of change in surface geometry.

b. If the item being tested has many components, those subjected to the greatest load or changes in load should be examined by the photoelastic method. Inspect these components to determine which areas will be tested, and identify these areas by small marks made with a grease pencil or felt tip marker.

c. Remove paint and primer from the surface areas selected for examination.

d. Follow the manufacturer's instructions for all procedures related to contouring the "limp" plastic to the surface of the test item, curing times, and cementing the plastic to the test item (or calibration specimen).

e. Re-assemble the test item (if it has more than one component), and prepare for testing. During re-assembly, protect the plastic from impact with hard objects and from heat due to flame or sliding contact.

NOTE: If, during step d or e, the plastic becomes damaged, and such damage would affect test results, discard it and formulate new plastic.

3.3 Photoelastic Equipment. Assemble the photoelastic equipment to measure stress.

a. For tests in which the photoelastic equipment (Figure A-2, Appendix A) will remain stationary and maintain the same view of the surface

area throughout testing:

      (1) Mount the equipment so that the plastic can be viewed through the analyzer during loading.

      (2) Mount a black plastic covering over the polariscope and test item (if the light cannot be dimmed) to darken the space containing the polariscope and the surface area to be viewed.

    b. For tests in which the photoelastic equipment will not remain stationary, but must move with the test item:

      Mount the photoelastic equipment in a fixture that can be attached to the test item but does not touch the area containing the plastic. NOTE: The fixture must be able to secure all electrical leads to the power source (or battery).

3.4 Photographic Equipment.

    a. For dynamic tests, mount a 16-mm movie camera and the polariscope in the same fixture on a single tripod. The frame speed for the camera should be at a rate to freeze the motion of the fringe pattern. All film in the camera before and after the test should be blacked out. Timing marks should be included on the film used.

    b. For static tests, mount a 35-mm still camera to the polariscope. Cover the reflection polariscope and area to be viewed with black plastic, if necessary.

    c. Perform all light meter readings and camera adjustments to obtain optimum photographic response of the fringe patterns during the test (use spotlight meter or through-the-lens meter system). For dynamic tests, conduct a trial run of the camera and frame speed to ensure proper lighting.

    d. All photographs (whether static or dynamic) of the fringes should include a standardized color card and an appropriate size ruler (nonmetallic) in an area adjacent to the fringes that are photographed.

    e. Photographic data should show the fine details of the fringe patterns of stress concentrations and the different direction of the maximum principal stress. All photographs of fringes or directions should contain identification of the loading condition (amount of load) and type of load (static, dynamic).

3.5 Loading.

3.5.1 Loading/Load Limits. During actual loading of the test item during the test, there can be no contact between the load and the birefringent plastic. While increasing the load to reach a maximum load condition for the static test, do not exceed the maximum designated load. Once the maximum load is reached, maintain it within ± 1 increment of the load scale of the machine until all pertinent performance test data are obtained.

3.6 Data Required. Record the following:

a. Type of aluminum or steel (calibration specimen); material properties: modulus of elasticity, E [kPa (psi)], Poisson's ratio, ν; width (near the midsection of the calibration strip); and thickness (near the midpoint of the calibration strip).

b. Make, model, and accuracy of reflection polariscope, tensile testing machine, and movie/still camera (if stress is to be measured during a time-varying load).

c. Birefringent plastic characteristics:

(1) Identification number for each batch mixed and contoured in conjunction with the test item, and location on test item where plastic was contoured.

(2) Average thickness of each piece of plastic (after curing) from a given batch and an identification number for each piece (if an individual measurement of thickness of a piece varies more than $\pm 5\%$ of the average thickness, record the measurement (thickness) for that point and the approximate location (by photograph) on the piece, as well as the average thickness without the point that exceeded the 5% limit).

(3) Identification number (recorded on the calibration specimen) for the batch from which each calibration strip was cut.

(4) Nominal values for the material properties: modulus of elasticity, E [kPa (psi)] and Poisson's ratio, ν of the birefringent plastic, and temperatures at which the plastic and cement were cured.

(5) Thickness of the calibration strip [t_q, mm (in)] (prior to cementing) at the center and total thickness (t_q, mm (in)] of the calibration strip, cement, and calibration specimen (after cementing) at the center of the calibration strip.

(6) For each calibration strip, using the format in Figure B-1, Appendix B:

Date
Temperature
Contour batch identification
Fringe order (N) corresponding to each load (kg)

4.   TEST CONTROLS.

a.   Review all instructional material (including system support packages) issued with the test item, and review reports of previous tests on similar items.

b.   Review the safety statement provided by the developer to determine whether any hazards have been identified. If hazards do exist, write the test plan to include subtests suitable for evaluating them.

c.   Make sure pertinent Standing Operating Procedures (SOPs) are at the test site.

d.   Make sure all personnel involved in testing are thoroughly familiar with provisions of SOPs and are fully capable of implementing them before any testing is begun.

e.   The line of sight from the center of the analyzer (Figure A-2, Appendix A) to the point on the surface of the birefringent plastic should be normal to the surface at the point of interest, generally within 15° (Figure A-3, Appendix A).

f.   Enough stress measurements at individual points should be made to identify all fringes and the signs (i.e., either tension or compression) of the stress at a free edge (such as a hole).

g.   Record any changes in meteorological conditions (if the test is being conducted outside) or any changes in temperature while the performance test is being conducted.

5.   PERFORMANCE TEST. Photoelasticity is a visual full-field technique for measuring the strains and stresses in parts and structures. When a photoelastic material is subjected to forces and viewed under polarized light, the resultant strains are seen as colorful fringe patterns. Interpretation of the pattern reveals the overall strain distribution, and accurate quantitative measurements can be made of the strain directions and magnitudes at any point.

Photoelastic coating combines the best features of strain gages and classical photoelasticity by providing:

a.   A visible picture of the surface stress distribution of the component.

b. Stress distribution which is accurately readable at any point for both direction and magnitude.

The photoelastic model is still the only method for three-dimensional analysis, but the surface-coating technique eliminates the difficulties in casting complicated models, yet permits the measurement of surface strains in the elastic or plastic ranges on structures, joints, welds, etc., previously inaccessible to photoelasticity.

5.1 Static Loading.

5.1.1 Method.

a. Zero Load. Using the reflection polariscope, visually inspect the areas coated with the birefringent plastic before placing any load on the component. (This includes any loads due to bolts/fastening devices necessary to assemble the component.)

b. Known Load. Gradually increase the load from zero to maximum. At the maximum load, visually inspect the birefringent coating.

c. Post-Loading. Gradually decrease the load from maximum to zero. At zero load, visually inspect the birefringent coating.

d. Post-Disassembly. After the test item has been disassembled and placed in the same position as when the plastic and cement on the components were curing, visually inspect the birefringent coating.

5.1.2 Data Required. Record the following for each group of inspections, using the format in Figure B-2, Appendix B:

a. Inspections.

(1) Date

(2) Temperature

(3) Test item/component (name) coated with birefringent plastic

(4) Location (specific area of component on which plastic was contoured)

(5) Point (specific point within the above location)

(6) Fringe order (N) (data obtained directly from the reflection polariscope when the line of view of the analyzer (Figures A-2 and A-3, Appendix A) is normal to the surface)

(7) Direction of maximum principal stress (θ) (measured in a ccw direction from the horizontal when facing the photoelastic coating, in degrees).

    b. <u>Photographic</u>.

        (1) Fringe patterns

        (2) Directions of the maximum principal stress for every 15° (i.e., 0°, 15°, 30°, 45°, 60°, 75°), unless there are only one or two directions.

5.2 <u>Dynamic Loading</u>.

5.2.1 <u>Method</u>. While the test item is at rest (before any dynamic load-ing), start the movie camera, and with the least delay, begin dynamic loading. When the dynamic loading is terminated, stop the camera as soon as possible.

5.2.2 <u>Data Required</u>. Record the following for each dynamic loading shown on the film:

    a. Date and time

    b. Object used to perform dynamic loading

    c. Loading rate

6.   <u>DATA REDUCTION AND PRESENTATION</u>. Tabulate pertinent data recorded in Paragraph 3.6, and proceed.

6.1 <u>Calibration Constants</u>. Determine the calibration constant (K) for each calibration strip by the following method:

    a. .For each load used in the calibration test, the difference be-tween the maximum principal strains $(\xi_1 - \xi_2)$ is:

$$\xi_1 - \xi_2 = \frac{1 + \nu_b}{E_b} \times \frac{P}{(1 + M)\, A_b}$$

when: $M = \dfrac{(t_T - t_b)\, E_q}{t_b\, E_b}$

when: ν = Poisson's ratio
         E = modulus of elasticity (kPa)
         t = thickness (mm)
         P = load on bar by tensile testing machine (kg)
         A = cross-sectional area (mm^2) = width x thickness

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subscripts:

> b = bar only
> q = calibration plastic strip only
> T = combination of plastic, cement, and bar

b. Plot $(\xi_1 - \xi_2)$ versus the fringe order (N) for each load (for all the loads used in the calibration test) on linear graph paper. Draw a single straight line which best lies between the points. The constant K is determined by computing the slope m of this straight line and multiplying M by t_q [mm (in)]. An example is given in Appendix C.

6.2 _Stresses_. Determine the stresses as follows:

a. For points not on a free edge:

$$\tau = \frac{E_c}{1 + v_c} \frac{KN}{2t_\rho} \ [kPa \ (psi)]$$

when: τ = maximum shear stress, kPa (psi)
       t = thickness of plastic at point of measurement (mm)

subscripts:

> ρ = plastic on which the measurement is being made
> c = component itself

b. For points on a free edge:

$$\sigma[kPa) \ (psi)] = \frac{E_c}{1 + v_c} \frac{KN}{t_\rho} \ , \ \text{if the direction of the maximum principal stress is parallel to the edge}$$

$$= -\frac{E_c}{1 + v_c} \frac{KN}{t_\rho} \ , \ \text{if the direction of the maximum principal stress is perpendicular to the edge.}$$

when σ = the stress tangential to the free edge [kPa (psi)] rounded to the nearest 6895 kPa (1000 psi).

c. For points where yielding is known to have occurred (i.e., where the computed τ or σ has exceeded the shear strength or yield strength of the component material) the data are presented in terms of strain only.

$$\xi_1 = \xi_2 = \frac{KN}{t} \left[\frac{mm}{mm} \ \left(\frac{in}{in} \right) \right]$$

when $\xi_1 - \xi_2$ represents the sum of the elastic and plastic strains.

6.3 <u>Photographic Data.</u>

6.3.1 <u>Static Test.</u> All photographs will be in print form, with the loading condition included on the photograph.

b. <u>Photographs of Fringe Patterns Only.</u> Representative stresses and direction of maximum principal stress will be labeled on the photographs and the corresponding points identified.
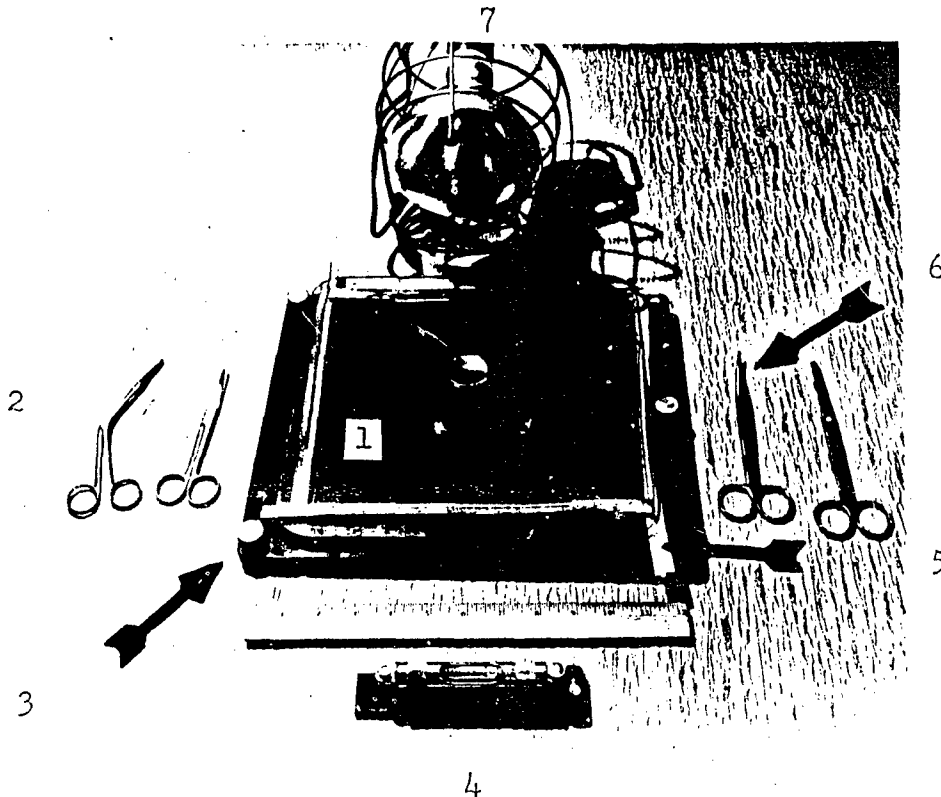
c. <u>Photographs of Directions of Maximum Principal Stress Only.</u> The directions of maximum principal stresses should be labeled.

6.3.2 <u>Dynamic Test.</u> The frames showing the maximum loading and maximum stresses will be in print form. Representative values for stresses and directions (of the maximum principal stress and corresponding points) should be labeled on the photograph. The photograph should also include a description of when (and where, if applicable) this maximum stress and load occurred.
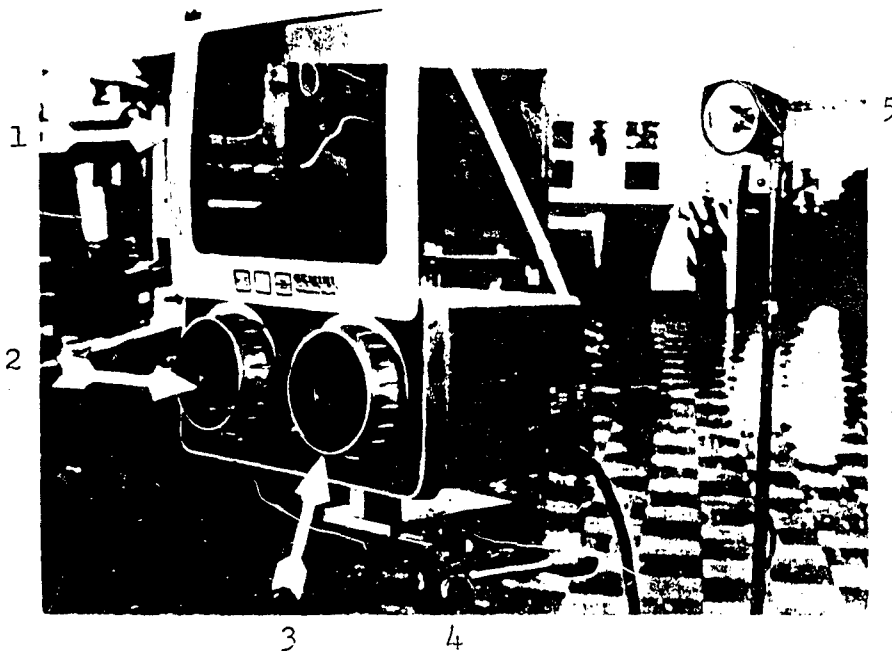
APPENDIX A

EQUIPMENT

1. Contouring mold (used to contain the liquid plastic when first mixed while it is curing to a mechanically "limp" phase)
2. Elbow surgical scissors (used to cut plastic while it is lying on a surface)
3. Adjusting screws to level plate
4. Machinist's level
5. Silicon rubber mold frame (used to contain the plastic while in liquid form) .
6. Curved surgical scissors (used to cut a curved path through the plastic)
7. Infrared lamp (used to heat resin and hardener and to warm the surface of the contouring mold)

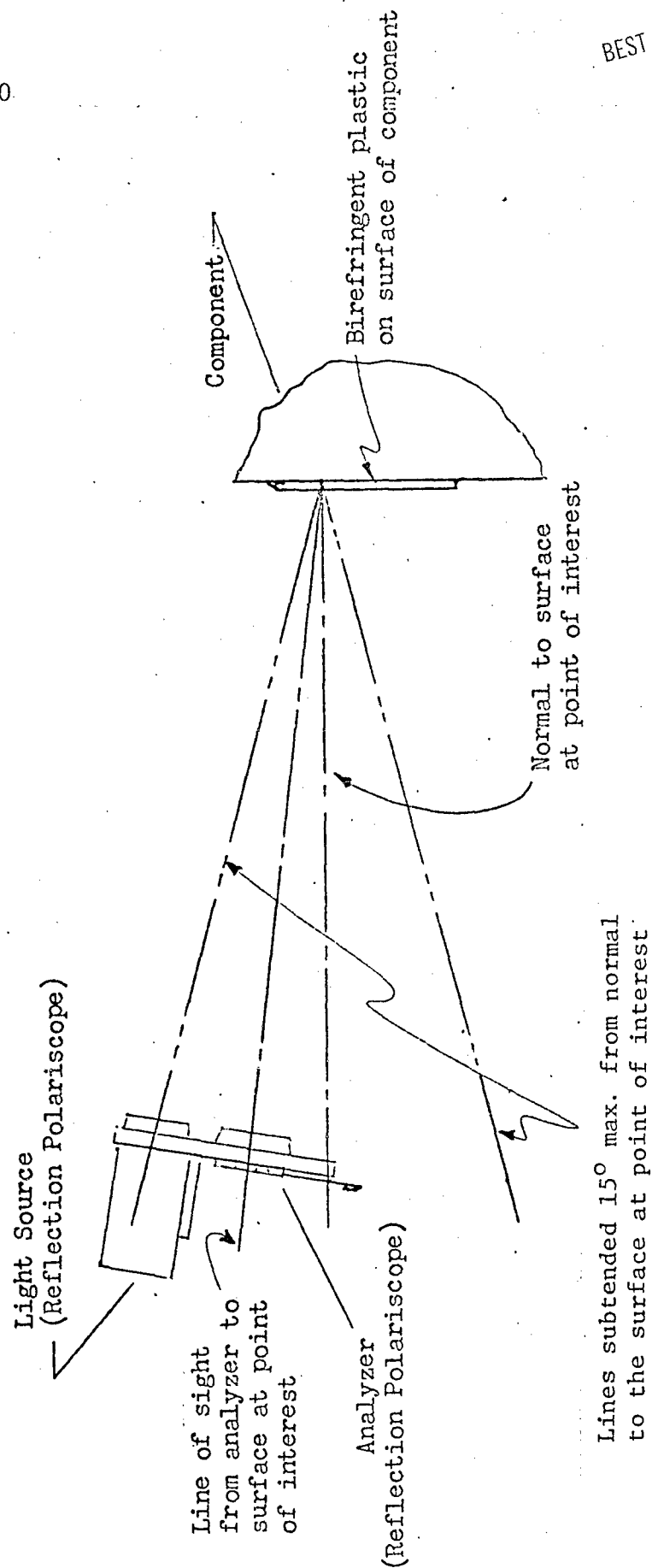Figure A-1. Photoelastic Analysis Equipment.

1. Circular polarizing screen
2. Analyzer (or viewer) side of reflection polariscope
3. Light source side of reflection polariscope
4. Tripod for polariscope
5. Extra light source (600-watt) and tripod (used only if necessary to view larger area

Figure A-2. Reflection Polariscope and Extra Light Source.

Component

Birefringent plastic on surface of component

Normal to surface at point of interest

Lines subtended 15° max. from normal to the surface at point of interest

Light Source (Reflection Polariscope)

Line of sight from analyzer to surface at point of interest

Analyzer (Reflection Polariscope)

Figure A-3. Limits of Line-of-Sight from Analyzer to Surface of Component.

APPENDIX B
DATA COLLECTION SHEETS

Data Sheet for Calibration Test -

Project _____

Date _____   Temperature _____°C (°F)[1]   Engineer _____

Batch ID _____

Load[2] kg (lb)	$(\epsilon_1 - \epsilon_2)$[3] Calculated	N[4]

Batch ID _____

Load kg (lb)	$(\epsilon_1 - \epsilon_2)$ Calculated	N

Batch ID _____

Load kg (lb)	$(\epsilon_1 - \epsilon_2)$ Calculated	N

Batch ID _____

Load kg (lb)	$(\epsilon_1 - \epsilon_2)$ Calculated	N

[1]Temperature in vicinity of aluminum bar. (Cross out unit that is not applicable.)
[2]Load applied by tensile testing machine.
[3]$\epsilon_1 - \epsilon_2$ = Difference between principal strains (para 6.1a).
[4]N = Fringe order as determined by reflection polariscope (para 5.1.2.a(6)).

Figure B-1. Data Sheet for Calibration Test.

Data Sheet for Photoelastic Stress Analysis

Project _____   Date _____   Engineer _____

Component _____   Temperature _____°C (°F)[1]

Load[2]	Point[3] ID	N[4]	θ [5]	Notes

[1]Cross out unit that is not applicable.
[2]Load applied to the component or to the entire system (force).
[3]Specific point on the component in which the measurements are being made.
[4]N = Fringe order measurements (para 5.1.2.a(6).
[5]θ = Direction of the maximum principal stress measured from the horizontal in a ccw direction when facing the item (degrees).

Figure B-2. Data Sheet for Photoelastic Stress Analysis.

APPENDIX C
EXAMPLE OF DETERMINING AND USING K FROM THE CALIBRATION TEST

Data for an aluminum bar:

$$E_b = 10^7 \text{ (psi)}$$

$$V_b = 0.32$$

$$t_b = 0.25 \text{ in.}$$

Data for birefringent plastic (calibration strip only):

$$E_q = 4.2 \times 10^5 \text{ (psi)}$$

$$V_q = 0.36$$

$$t_T = 0.405 \text{ (in.)}$$

1. From the equation in paragraph 6.1a and the above values

$$M = \frac{(0.405 - 0.25)\ (4.2 \times 10^5)}{(0.25)\ (10^7)}$$

$$M = 0.026$$

2. Substituting M into the expression for $\epsilon_1 - \epsilon_2$ in paragraph 6.1a

$$\epsilon_1 - \epsilon_2 = \frac{1 + 0.32}{10^7} \times \frac{P}{1 + 0.026} \times \frac{1}{1 \times 0.25}$$

$$\epsilon_1 - \epsilon_2 = 5.15 \times 10^{-7}\ P$$

3. Given the following data (load on the bar, corresponding fringe order measurement) from a calibration test the calculated $(\epsilon_1 - \epsilon_2)$'s are:

Load (P) (1b)	N	$(\epsilon_1 - \epsilon_2)$ (10^{-3}) (in/in)
2010	0.63	1.04
2980	0.96	1.53
4415	1.41	2.27
5860	2.05	3.02

4. Figure C-1 shows the above data plotted in accordance with paragraph 6.1b.
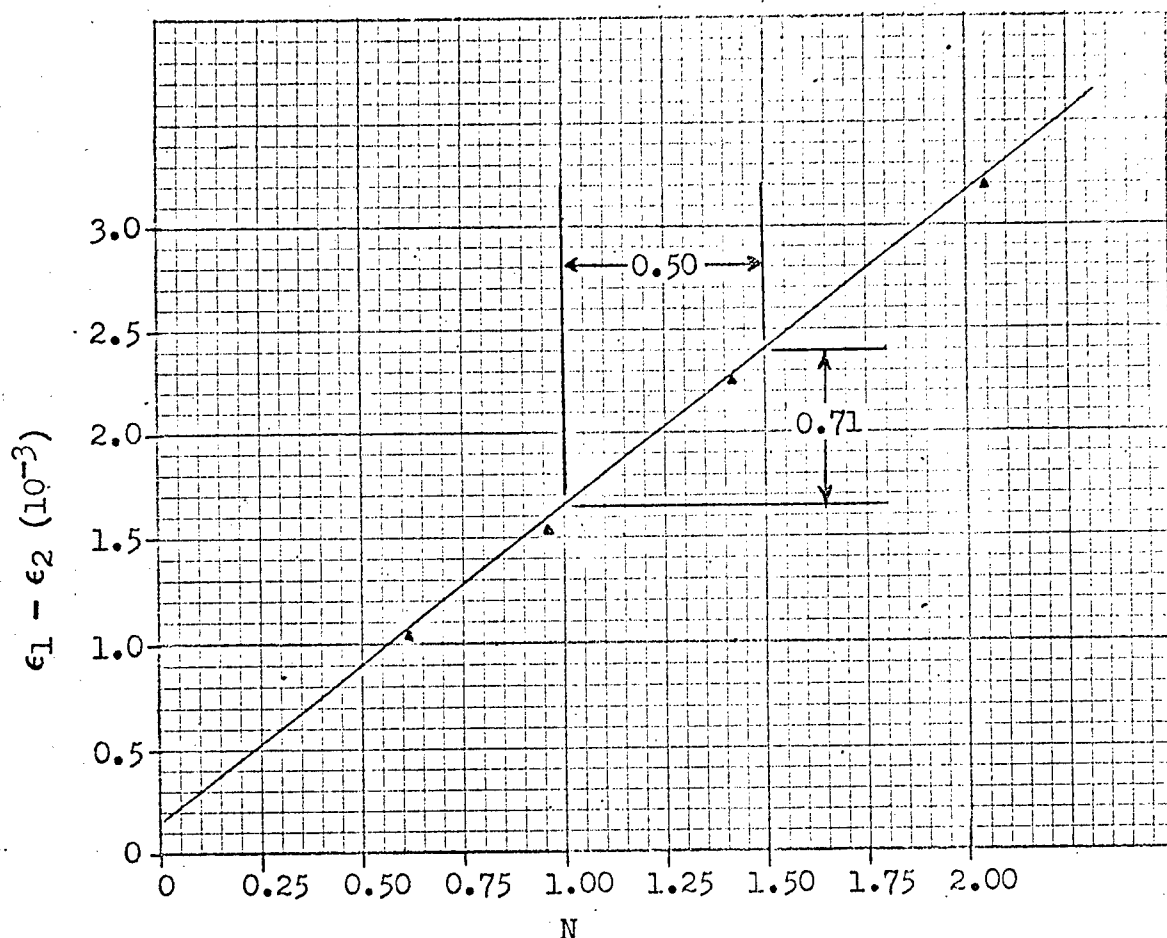
Figure C-1. Plot of Difference in Maximum Principal Strains
($\epsilon_1 - \epsilon_2$) Versus Fringe Order (N).

5. Taking the values (to determine the slope (m) of the straight line) from the graph,

$$K = mt_q = \frac{0.71 \ (10^{-3})}{0.50} \ (0.125)$$

$$K = 1.78 \times 10^{-4} \left(\frac{strain}{fringe} \right)$$

6. From test data on a plastic piece ($t\rho$ - 0.120 inch) which came from the same batch as the above calibration strip, a measurement of N = 1.23 was made at a point not at a free edge. The component was of steel,

$$E_c = 30 \times 10^6 \ psi, \ V_c = 0.28,$$

the maximum shear stress T is

$$T = \frac{30 \times 10^6}{1 + 0.28} \times \frac{(1.78 \times 10^{-4}) \ (1.23)}{2(0.120)}$$

$$T = 21 \times 10^3 \ psi.$$